



Catchment metabolism: Integrating natural capital in the asset management portfolio of the water sector



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ABSTRACT

The policy of the water sector demands integrated and resilient asset management. The majority of current research focuses on urban or community asset systems. To provide a fully integrated approach, one needs to delineate the focus of asset management at a catchment scale, to include the natural capital. The research described in this paper introduces such an approach, with the Environmental Regional Input-Output (E-RIO) analysis at its core.

The novelty of the work is the conceptualisation of a catchment as a complex asset system, comprising of multiple subsystems. This expands the application of Industrial Ecology and functional modelling techniques in Integrated Catchment Management and Water Accounting. The Catchment Metabolism modelling schema created in this paper serves asset, water resources and catchment management purposes. The schema forms the grounds for structured collaboration among experts for integrated water resources planning and decision-making. In this paper the process of creating the modelling schema along with the techniques used are presented. A 'live' industrial example from the UK water sector (Poole Harbour Catchment) is used to demonstrate its application.

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1. Introduction

The World Forum for Natural Capital (i.e. the world's natural systems, such as aquatic systems land, and their deriving services) relates the poor management of the natural environment with catastrophic consequences on ecosystems productivity, human wellbeing and financial resilience (Natural Capital Initiative, 2015). In these grounds, the United Nations Natural Capital Declaration (NCD, UNEP, 2012) demonstrated the commitment of financial institutions of the private and commodity sectors to integrate Earth's natural assets in their reporting, accounting and decision-making. A considerable number of business initiatives have emerged since, aiming at the integration of natural capital in financial decision-making with special focus on awareness raising, business encouragement and publications (Maxwell et al., 2014).

An essential action requested under the NCD is for companies to disclose the nature of their dependence and impact on Natural Capital through transparent qualitative and quantitative reporting. Several policy initiatives (e.g. United Nations Statistic Division

UNDS, 2012) and programs (e.g. World Bank Wealth Accounting and Valuation of Ecosystem Services, WAVES, <https://www.wavespartnership.org/>) provide a basis for resources accounting through the application of accounting techniques in environmental science and the management of natural flows, but these focus on the economic valuation of natural capital and its ecosystem services. Limited work has been undertaken for the evaluation of whole systems and for the integration of accounting methods into systems modelling that would allow for the reporting and analysis of the mutual relationships among built, financial and natural assets.

Recent works (Ma et al., 2015; Paterson et al., 2015; Xue et al., 2015; Rudell et al., 2014) demonstrate the essence of transcending disciplinary silos for the development of systems approaches in integrated water resources management. In these studies, the focus is on urban water systems at city or community level; yet their research findings apply to multiple water systems. These works demonstrate the need to consider and integrate the natural water cycle in urban planning and policy by creating consistent and robust methodologies (Paterson et al., 2015; Xue et al., 2015; Norton and Lane, 2012). These works also indicate that more research is needed to implement the principles of

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systems thinking in the complex water environments, while the development of more practical applications and case studies is crucial to achieve it.

The creation of whole system approaches would enable multi-viewpoint analysis as well as combined systems' analysis. This would prove of particular use for the commodity sector, e.g. the water industry, as the delivery of their services depends on the provision of both physical and natural assets. The UK water sector is officially encouraged to become more resilient by adopting integrated approaches to their asset management with the purpose being to achieve a balance between financial costs and environmental impacts (Department for Environment Food & Rural Affairs, 2016; OFWAT, 2015; UKWIR, 2014). In the meanwhile, the creation of approaches that would enable businesses to integrate natural capital in their planning and practice has been recognised as a priority area for future research (Natural Capital Initiative, 2015).

The research described in this paper responds to the demand for approaches that allow for transparent reporting on the dependencies of the water sector on natural assets. The 'Catchment Metabolism' (CM) concept and modelling schema, a structured, transdisciplinary approach for modelling catchments systems and gathering data for integrated asset management purposes is introduced. The synthesis of well-established methods and tools available from other disciplines are used in synergy to shape the basis for integrating natural capital in the strategic planning schemes of the water industry. The whole-system approach developed is based on the principles of integrated catchment management (ICM), water accounting and environmental regional input-output analysis (E-RIO). It builds on a combination of concepts and methods that have been reviewed and approved for their ability to address sustainability issues (Little et al., 2016; Ma et al., 2015; Paterson et al., 2015; Xue et al., 2015; Rudell et al., 2014), and shape optimised planning strategies (Ma et al., 2015; Rudell et al., 2014; Daniels et al., 2011) for better resource efficiency. The CM schema offers a conceptual approach where researchers and end users can conceptualise catchment systems and their processes, which is essential for integrated water resources management (Macleod et al., 2007).

The outputs of this research will be used by our industrial partner to demonstrate they are meeting the UK national policy demands for integrated and resilient asset management. The CM modelling schema responds to the need for evidenced based approaches, which can be used in the practical application of sustainability and systems thinking principles in the water industry. It is tailored to address current challenges of the water sector and its design enables practitioners to apply research advancements. One of the advantages of the schema is that systems-thinking is required, hence, collaboration among experts and stakeholders within the water sector occurs. This reflects the transdisciplinary nature of the work.

Despite its structured and comprehensive design, it is a rather sophisticated and data intensive methodology which requires collaboration among experts and the automatising of processes in a later stage. The application of the schema in diverse typologies of catchments is required to evaluate its flexibility and highlight areas for future improvement. More case study applications may provide further practical insights and facilitate the integration of the approach in every day practice.

The paper is organised as follows: after the introduction, the system boundaries of the research and the creative process for identifying the appropriate techniques used to formulate the underpinning methodology are described. The synthesised approach is then presented and the Catchment Metabolism modelling schema is applied to a 'live' water sector case study. The paper concludes by discussing the future steps for the practical application of the schema in the UK water sector.

2. Setting the system and research boundaries

The catchment is selected as the unit of analysis as the most suitable scale to assess water sustainability (Papacharalampou et al., 2015; Nafi et al., 2014; Hester and Little, 2013) and the interactions between the different types of capital (Pérez-Maqueo et al., 2013). In this paper, catchments, as defined from a hydrological perspective, (i.e. the geographical area within which a surface watercourse or a groundwater system delivers its water) are the regional scale of interest. They are defined as hybrid integrated systems, which include both natural elements (biosphere) and infrastructure (technosphere); thus, they are defined and conceptualised as complex asset systems. Following the principle of integrated water resources management and ecosystem services (Cook and Spray, 2012), the ecosystem is considered as a stakeholder who plays an active role within the boundaries of the catchment.

The Poole Harbour Catchment (PHC) was selected as an example catchment and is used throughout the paper to show the application of the modelling schema. Poole Harbour in Dorset (South-West England) has a catchment area of 820 km² with predominantly agricultural land use (80% of land use, EA, Nitrogen Reduction Strategy report, 2013). The area contains many sites of local, regional, national and international importance and is designated as protected area under a number of conventions and directives. The inflowing rivers in the harbour cover a major drainage area. The substantial part of the catchment lies to the west and is drained by the River Frome and the smaller River Piddle. To the north and south are the much smaller catchment areas of the Sherford River and Corfe River respectively, and also the catchments of several minor streams (Fig. 1).

The PHC was selected as a pilot area to participate in the national Catchment Based Approach initiative launched in 2012. Investigation of the catchment's environmental pressures and the status of its watercourses revealed that nitrogen pollution is its key environmental issue (Environment Agency, Nitrogen Reduction Strategy report, 2013).

To date, efforts to reduce nutrient levels in the watercourses have mainly focussed on point-source inputs of nutrients and Wessex Water Services Ltd (WWSL) have invested in physical infrastructure solutions such as the addition of phosphorus and nitrogen removal at sewage treatment works in order to address the problem and meet statutory standards. While point-source loads of nitrogen into Poole Harbour have reduced significantly, there have not been equivalent efforts devoted to diffuse pollution from farming and other land use, which have been identified as the major contributors of nitrogen to the Harbour. However, the influence of background factors (e.g. geology) in combination with the current nitrogen management in the catchment has not yet resulted in evident declines in the Harbour's nitrate concentrations. Work to address the diffuse pollution has been initiated by WWSL which focusses on partnership-based catchment management for the reduction of nitrates in groundwater and the improvement of the status of surface water.

A more holistic approach, informed by analysis of the system's inputs and outputs, is required in order to improve decision-making and in time, the overall condition of the Poole Harbour and its catchment (Papacharalampou et al., 2015).

3. Creating the catchment metabolism modelling schema

The Catchment Metabolism (CM) schema is designed on a robust, transdisciplinary basis but is also practical, so that it can be easily used from water practitioners. Its feasibility to serve everyday practice is validated through an industrial case study in

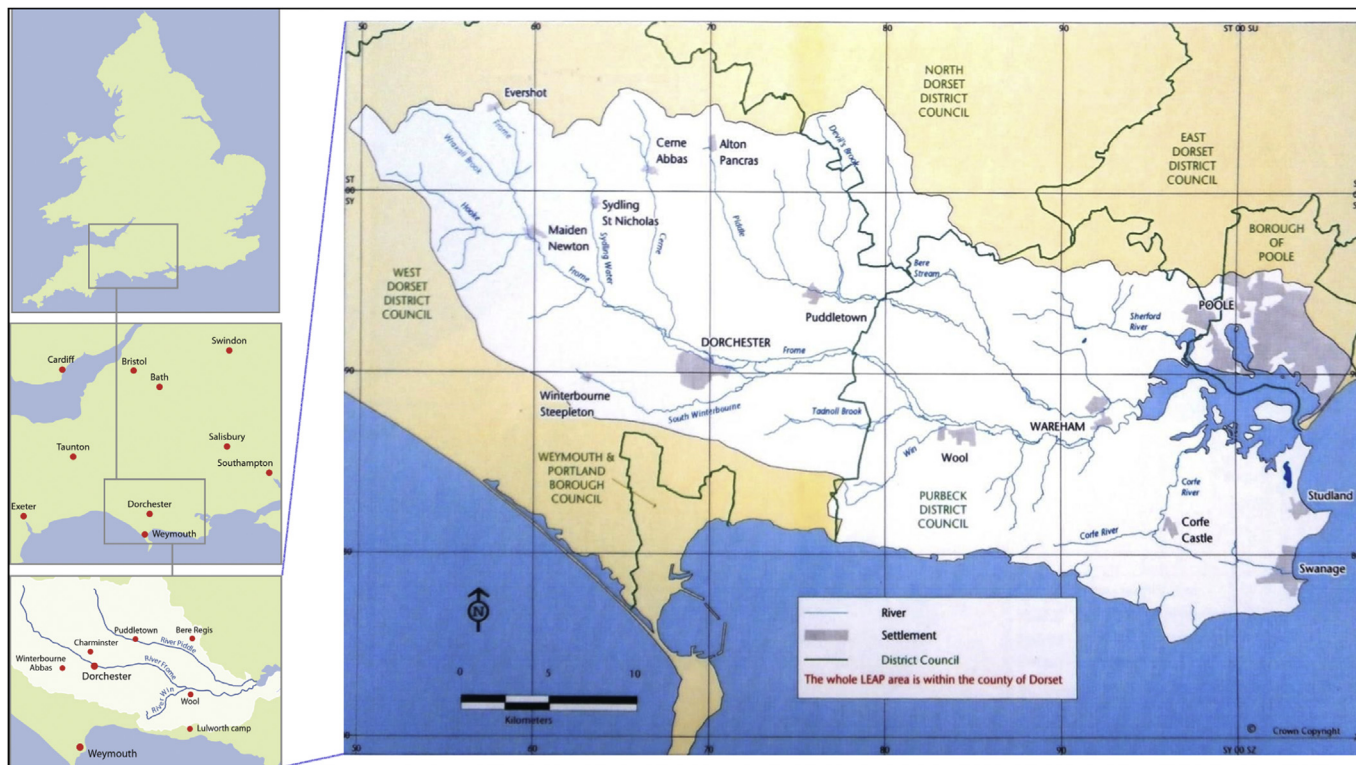


Fig. 1. The Poole Harbour Catchment, its main settlements and inflowing rivers in the Harbour. (Adapted from the EA report, 2013).

collaboration with the regional water company. The section gives an overview of the rationale of the creation of the modelling schema and its underpinning concepts and tools. The explanatory brainstorming diagram outlines the synthesis of the transdisciplinary methodology (Fig. 2). The term 'transdisciplinary' is used to describe the approach that involves the collaboration between two or more disciplines with high levels of interaction, causing the development of a new conceptual, theoretical and methodological frameworks, after Leavy 2011. Further, for the undertaken research described in the paper, the concept of transdisciplinarity is utilised as a means to bring policy requirements into academic research (Stavridou and Ferreira, 2010; Pohl, 2008).

The divergence of the work and the lack of previous relevant approaches in the field of asset management required an extensive literature review to be performed. This mainly focussed on

identifying and analysing the tools for integrated environmental-economic accounting widely used in other fields and been applied in different scales (e.g. infrastructure asset systems, community, city).

Transdisciplinary approaches have emerged as a research process to address the complexity of systems and require the methods to be constructed around the research goal (Leavy, 2011; Walter et al., 2007). For the formulation of the CM, it was hypothesised that the currently analysed tools could be applied for the creation of catchment-based approaches for asset management purposes. For the hypothesis to be held true the tools need to account for both the natural and the built capital on a catchment basis.

The initial intention was to create an approach that would enable to achieve the research goal through the application of life cycle management and the tool of Life Cycle Assessment (LCA) at a

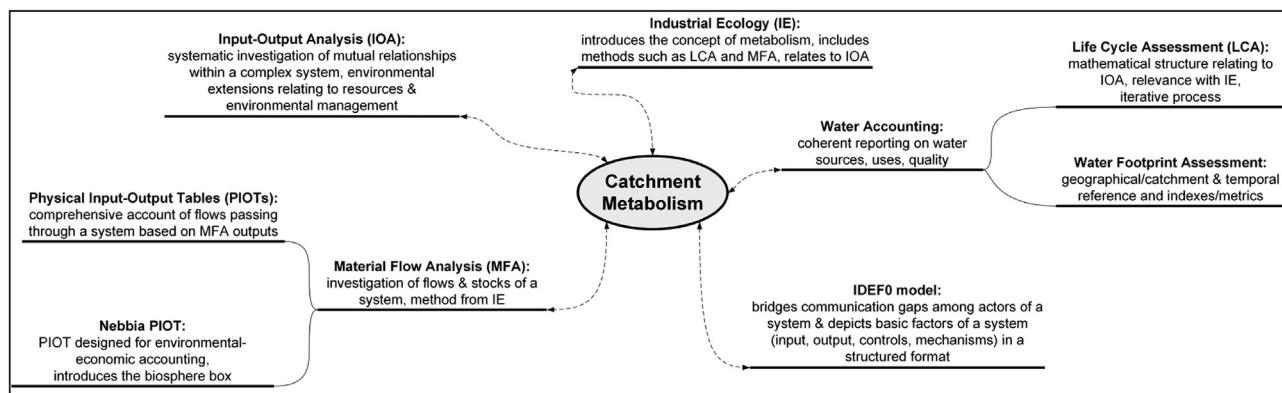


Fig. 2. The formulation of the Catchment Metabolism modelling schema based on a robust synthesis of methods available for systems engineering and environmental-economic flow accounting.

catchment scale. To overcome the limitations of LCA in terms of its spatial reference and applicability at delineated geographical areas (Baumann and Tillman, 2004), a number of other tools were orchestrated. The project then explored how Industrial Ecology (IE) – which is the research field underpinning LCA – can be used for the creation of the CM schema. In order to do this, the development of the field of IE into other widely used concepts was explored using a detailed literature search. Four main techniques were identified: Water Accounting, Input-Output Analysis (IOA), Material Flows Analysis (MFA) and IDEFO (a compound acronym deriving from *Icam DEFinition for Function Modelling*, National Institute for Standards and Technology, 21 December 1993). The structures and main knowledge blocks of a number of concepts and tools were analysed and then synthesised (i.e. synergetic research approach and transcendence) based on their strengths and contributions to specific objectives of the modelling schema, in order to create new knowledge (i.e. innovation) and serve pragmatic challenges (i.e. issue-centric). All these attributes qualify the modelling schema as transdisciplinary.

The overview of the concepts and techniques is presented in this section, along with the linkages among them.

Industrial Ecology (IE) outlines the analogy between the industrial system (anthroposphere) and the natural environment (biosphere) and consists a framework towards practical sustainability. It has been applied for the optimisation of material cycles within the industrial systems as it serves for the development of symbiotic relationships among industries and treats the industrial system as a complex organism with unique metabolic rules (Suh and Kagawa, 2005). The basic methodologic concept of IE is that of ‘industrial metabolism’, which is a descriptive and analytical concept based on the principle of the conservation of mass applied for the understanding of the complex patterns and dynamics of flow and stocks of material and energy within the industrial system. Industrial Metabolism has been widely applied in the urban context, as summarised by Clift et al. (2015) and involves a range of methods (e.g. Life Cycle Assessment, Material Flow Analysis) which have served planning and development purposes especially in the form of regional flow analysis (Brattebø, 2003; Erkman, 2003).

Despite the recognised value of the concept of IE in strategic sustainable development (Korhonen, 2004), its applications in water-related studies is rather limited (Núñez et al., 2010). Recent water-related IE applications focus on the development of indicators for effective water management (Ziolkowska and Ziolkowski, 2016; Farreny et al., 2013), the formulation of models for water demand and pricing (Dharmaratna and Harris, 2012; Morales-Pinzón et al., 2012) or the environmental assessment of municipal and urban systems (Lemos et al., 2013; Oliver-Solà et al., 2013) and cultural services (Farreny et al., 2012).

Life Cycle Assessment (LCA) is technique of IE used to quantify the environmental impacts associated with all the stages of a product, service or process from cradle-to-grave and has gained popularity as a sustainability assessment method (Guinée et al., 2011), as evidenced by the increasing number of publications and databases supporting its implementation. Until recently, water flows have been neglected in freshwater inventories and impact-assessment studies. The last few years, however, there has been a growing interest in the field of *Water Accounting* followed by the development of metrics and indicators (Kounina et al., 2013) which can assist communication among water-related scientists, policy-makers and stakeholders. *Water Accounting* can be described as the systematic process of identifying, quantifying, reporting, and publishing information about water as a resource (e.g. sources and uses of water). The information produced needs to be coherent and harmonised in order to prove useful to decision makers within the water sector.

There are two main parallel developments in the water accounting community: water footprint network (WFN, Hoekstra et al., 2011) and Life Cycle Assessment (LCA)-water or Water Footprint Standard (ISO/DIS 14046, 2014). As analysed in Boulay et al. (2013), both methodologies aim at helping practitioners to manage and sustain water resources. However, the quantitative indicators obtained from LCA-type and WFA-type approaches remain hardly comparable: LCA is largely focused on a product, whilst the crux of WFA is water management in a given geographic area. Over the last years, a number of reviews on both methodologies have been performed (Kounina et al., 2013; Berger and Finkbeiner, 2010) alongside critiques (Wichelns, 2015; Chenoweth et al., 2014; Tillotson et al., 2014; Yang et al., 2013) mainly in regards to the limitations of the methodologies in terms of their policy relevance, data accuracy, methodological approaches and conceptual consistency. Attempts to pursue methodological harmonisation between LCA and footprint research are strongly encouraged in the literature.

Recent case studies (e.g. Zhi et al., 2014; Feng et al., 2011; Yang et al., 2013; Yu et al., 2010) have focussed on the combined use of water footprint with *Input-Output Analysis (IOA)* as a means to inform regional or national decision-making.

Input-Output Analysis (IOA) was introduced in 1930's as an analytical framework to investigate the economic transactions between the various sectors of an economy. Since, it has evolved and been widely applied in a large number of studies and fields (Feng et al., 2011) as a method for systemically quantifying the mutual interrelationships within a complex economic system and has proven valuable in IE studies for the compilation of statistical data at a national or sectorial level (Suh and Kagawa, 2005). Economic input-output modelling has also been used for environmental systems analysis. Environmental input-output analysis (E-IO) and its regional extensions (Environmental Regional Input-Output, E-RIO) have emerged as popular and promising frameworks for sustainability analysis (Wiedmann et al., 2011; Hawkins et al., 2007). E-IO enables assessment of natural resources and pollutants embodied into goods and services and in their supply chains along the economy. Regional input-output (RIO) analysis enhances this capability by mapping the geography of the resource use, emissions and other environmental effects and provides a spatially-explicit framework than can assist in assessing environmental impacts. This ability of ‘geo-position’ is vital for assessing sustainable scale and impacts for many environmental resources, especially for water, since its sustainability and management is considered at a local level (Daniels et al., 2011). The recent applications Zhi et al., 2014; Feng et al., 2011; Yang et al., 2013; Yu et al., 2010; Zhao et al., 2010) show progress in the integration of geographical information and process-based water footprints (WFs) in input-output models and accounting tables.

Physical Input-Output Tables (PIOTs) are accounting tools which provide a comprehensive description of anthropogenic material flows (e.g. material and energy flows) passing through the economy of a country. For their construction the mass balance principle is utilised and the economic system is depicted as being embedded in the larger natural system. A *Material Flow Analysis (MFA)* study can form the basis for the quantitative information necessary to construct a PIOT. MFA has been widely applied for assessing the material base and resource throughput the national economies (Giljum and Hubacek, 2009; Brunner and Rechburger, 2003) and its applications mainly include the quantification of aggregated resource inputs and outputs of economic systems and are performed according to its methodological guidebook (Eurostat, 2001).

The result of the transferral of MFA data to the PIOT is that the output produced by each production chain is split among various columns, where each column refers to a specific economic sector. A

full PIOT can show the material flows between sectors (industry by industry) or the materials required to transform other materials in the production process (materials by materials or commodity by commodity). In general, a PIOT is a tabular scheme in which a certain number of economic activities or sectors are represented by their material input and output. Nebbia (2000, 1975) outlines a type of PIOT aiming to capture the circularity of industrial metabolism in terms of a “natural history of commodities” – from the environment, and back to the environment. At the heart of Nebbia’s PIOT is an economic-ecologic accounting carried out by the principles of commodity science to determine the intersectoral flows between and within the biosphere and the technosphere. The distinguishing feature of this approach is that also the biosphere, not just an economic system is divided in sectors, between which intersectoral flows may occur. As analysed in De Marco et al. (2009), the general formation for the construction of a Nebbia’s PIOT can be synthesised in a table which is initially split in four different quadrants:

	Nature (i)	Technosphere (j)
Nature (i)	<i>aii</i>	<i>aij</i>
Technosphere (j)	<i>aji</i>	<i>ajj</i>

where *aii* represents flows within the biosphere, *aji* resources ‘sold’ from the biosphere to the technosphere (e.g. water used in production processes), *aji* material flows from the technosphere to the biosphere (e.g. waste disposed or emissions) and *ajj* commodities exchanged between different technosphere sectors (e.g. electricity ‘sold’ to production processes).

From this PIOT one can compute the ‘physical’ mass of materials absorbed by final consumption, including exports and stocks, minus the imports. However, its application to date excludes the mass of water which circulates through the natural and economic systems (e.g. embedded water in products). The major shortcoming of PIOTs is that all flows are accounted in one single unit; thus, the consideration of the qualitative differences of materials flows in terms of different environmental impacts is very limited (Giljum and Hubacek, 2009) and more research needs to be undertaken to overcome this issue.

Undertaking the steps to construct a PIOT that would represent outputs of the sectors within the complex catchment system, a tremendous amount of data is required, along with the contribution of multiple experts. To overcome this challenge, a functional modelling language- *IDEFO*- is introduced in the schema. IDEFO (a compound acronym deriving from *Icam DEFinition for Function Modelling*, National Institute for Standards and Technology, 21 December 1993) is a method designed to model the decisions, actions, and activities of an organisation or a system. It has been applied, but is not limited, to topics such as strategic planning, hybrid systems design and business process reengineering (Feldmann, 1998) and has proven useful for handling complexity and bridging communications gaps between various actors involved in a system. Recent research (Settanni et al., 2015, 2014; Šerifi et al., 2009) highlights the applicability of the method across disciplines and sectors, for the development of modelling approaches for product service systems (PSS), for measuring performance and outcomes of asset systems and for designing software packages.

An IDEFO model (made of several IDEFO diagrams) depicts constraint, not flow. The graphical elements of IDEFO are very simple (Fig. 3)- just boxes and arrows. The syntax and semantics for both IDEFO diagrams and models are precisely defined in the FIPS

for IDEFO (FIPS PUB, 1983). Each activity box on an IDEFO diagram depicts the function described by the verb phrase written in the box. The arrows shown entering and leaving the boxes depict things that are needed or produced by the function. Unlike data flow diagrams, IDEFO model shows what controls each activity and who performs it, as well as the resources needed by each activity. Developing an IDEFO model is a step-by-step procedure which begins at the point which the author determines the basic model parameters: the purpose and the viewpoint. For the same system, different IDEFO models can be created, based on the selected viewpoint.

Summing up the creation of the Catchment Metabolism modelling schema, a structured, creative and transdisciplinary approach was followed and a number of concepts and techniques were synthesised. The concept of metabolism derives from the field of Industrial Ecology and has been used as the conceptual basis of the modelling schema. Material Flow Analysis (MFA) and its Physical Input-Output Tables (PIOTs) formulate the reasoning for flow accounting within the catchment systems and construct the format of the Catchment PIOT. The structure of the Catchment PIOT is based on the PIOT introduced by Nebbia (2000, 1975), which was originally designed to represent the inputs and outputs of economic activities (e.g. sugar production) or sectors (e.g. metallurgy) of an economy. For the Catchment PIOT, each of the stakeholders of the catchment is split into sectors. The flows captured in the PIOT are the outputs of the activities occurring among the sectors of the catchment. Input-Output Analysis (IOA) and its environmental extensions are used as tools to account for the multiple flows of the complex catchment system in a constructed approach. Water Accounting methods provide the metrics for water flow accounting in multiple systems. The IDEFO model has been selected to serve as a method to collect and depict information for the subsystems of the catchment and to bridge communication gaps among the experts involved in the process of integrated catchment management.

4. The catchment metabolism in practice

4.1. Constructing the catchment PIOT: a step-by-step process

The creation of the Catchment Metabolism (CM) schema is based on the combined use of the concepts and tools as analysed in the previous section. A number of steps are undertaken in order to depict and map the metabolism of the selected system. The Catchment Physical Input Output Table (Catchment PIOT) is

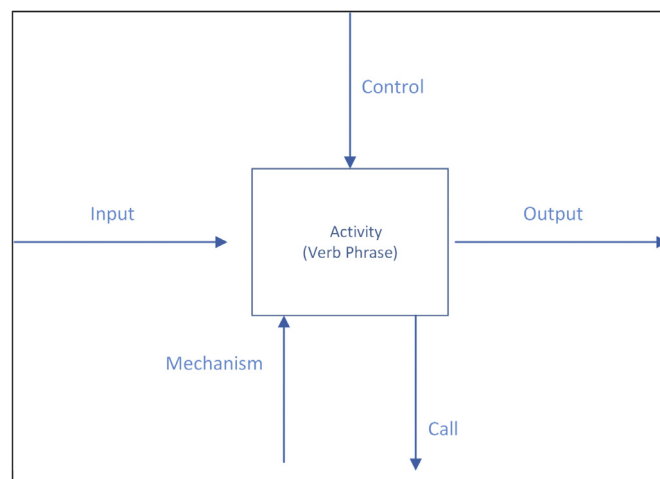


Fig. 3. IDEFO activity box.

constructed through a sequel of interlinked stages which add value to the modelling schema.

The Catchment PIOT is developed as a structured way to map the metabolism a catchment, which essentially refers to the inter-industrial relationships taking place within the system's boundaries. The metabolic relationships of the catchment compartments are mapped over a period of a year. This time scale has been chosen in order to serve practical and scientific purposes and also comply with the rules of the original PIOTs. The Catchment PIOTs can also be constructed for the wet and dry periods of each year, so that variations of the flows circulated in the system are depicted.

In order to gain insight in the natural processes occurring within the selected scale, the breakdown of the biosphere in its metabolic compartments is introduced in the Catchment PIOT, following the terminology of MFA. Therefore, the quadrant *aii* – which represents the flows within nature – is split into: Atmosphere (Air), Hydrosphere (Water), Pedosphere (Soil) and Lithosphere (Geology). This alteration provides a better understanding of the natural occurring processes of the ecosystem of a catchment which affect its economic activities, e.g. agriculture. As a result, one can fit in the PIOT the water volumes circulated within the catchment system; the water flows circulating in both biosphere and technosphere.

Following the example of the original PIOT, the first step to the construction of the Catchment PIOT is the performance of a Material Flow Analysis (MFA) of the catchment. A modified flow chart (Fig. 4) describes the catchment as an integrated system, based on the consequential relationships among its elements. Its focus is the water circulation within the system boundaries which assists in explaining the relations and interdependencies among its subsystems, both natural and artificial, serving mainly information display and communication purposes. Studying the water circulation allows for the identification of the main water-related activities which take place within the catchment's boundaries and their actors.

For the selected case study as described earlier in the paper, we observe the presence of three main water-related 'industries': Ecosystem, Water Company, Agriculture. In this catchment, the origin of water available for use in the technosphere (urban water cycle, agriculture) is mainly groundwater; surface water flows are also accounted because of the import of water trade volumes from adjacent catchments. These two activity categories produce different wastewater, in terms of its quality and quantity, as well as character, referring to point and diffuse pollution respectively. The quality of the return flows to the aquifers strongly depends on the intensity of agricultural activities. The infiltrated water is then

abstracted to re-participate in the water cycle and its quality, mainly in terms on nutrient load influences the intensity of the water treatment process, especially in relation to the energy consumed.

After the identification of the key water actors and the role of their activities within the catchment boundaries, the metabolism of the most critical subsystems needs to be studied. The criticality of the subsystems selected reflect both the scope of the work and the key-issues in the designated catchment.

IDEFO diagrams are produced for each the identified "industries" or actors, analysing the inputs, outputs, controls and mechanisms of their subsystems. The IDEFO model for the actor 'ecosystem' is produced as an exemplar analysis (Fig. 5). The water cycle is investigated as the main ecosystem function. Same principles and representations are to be used for the other critical subsystems of the catchment.

The IDEFO model analyses the subsystems of the catchment system and gives an overview of their main attributes: inputs, outputs, mechanisms and controls. In the first top-level diagram (A-0) the purpose and the viewpoint of the model are stated. Then, the main actors and their contributions towards achieving the scope of the model are presented (AO). In the next part of the model, the focus shifts to the internal anatomy of the actors involved (A1); in the example presented, the focus is on the natural environment and thus the three natural cycles are depicted. In the last part of the model (A11), the life cycles or their stages are broken down into the involved sectors, resulting in a pictorial factor analysis. For instance, choosing the natural water cycle as the focal point, the processes (evapotranspiration, percolation, infiltration, run-off) occurring within the subsets of the natural environment (atmosphere, pedosphere, lithosphere, hydrosphere respectively) are demonstrated followed by the factors that control the natural process (e.g. the porosity of the lithological formation controls the volume of the water infiltrated) and the mechanisms that result in the natural output (e.g. the capillary mechanism drives percolation).

The latter part of the IDEFO model (A11) shapes the Catchment PIOT, as the sectors and their processes formulate the columns of the produced table. Also, the information/data from the IDEFO model are transferred in the tabular format to build a sector by sector (sector x sector) PIOT (Table 1).

In a next stage, the cells of the Catchment PIOT are filled in using indexes from Water Accounting, where the output of each of the sectors (row) to the other sectors (column) are depicted. As a result,

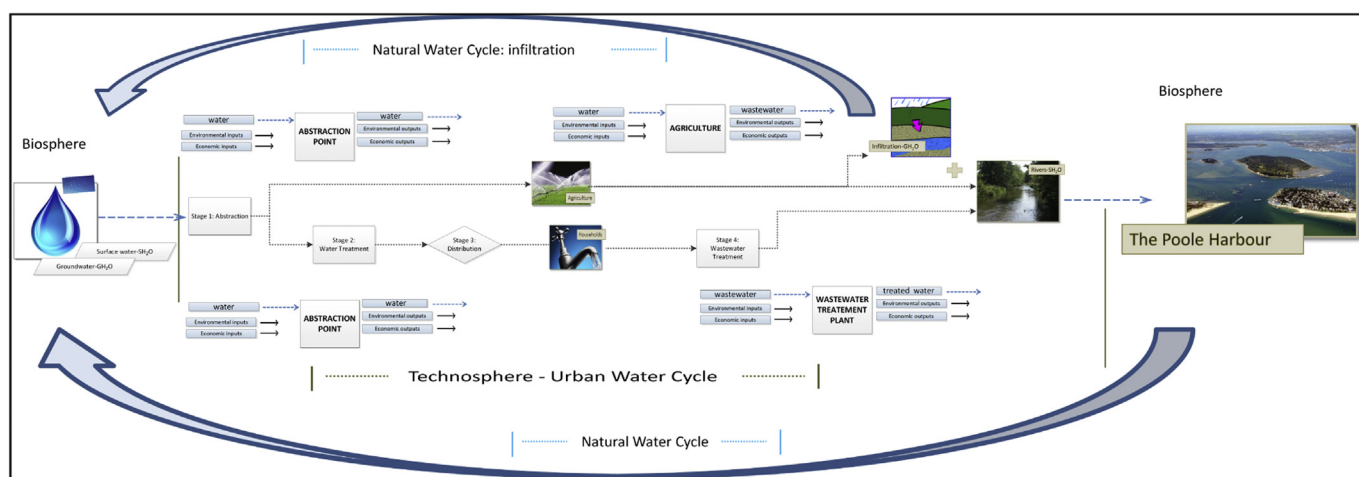


Fig. 4. The Poole Harbour Catchment as an integrated system and its main water-related actors and subsystems.

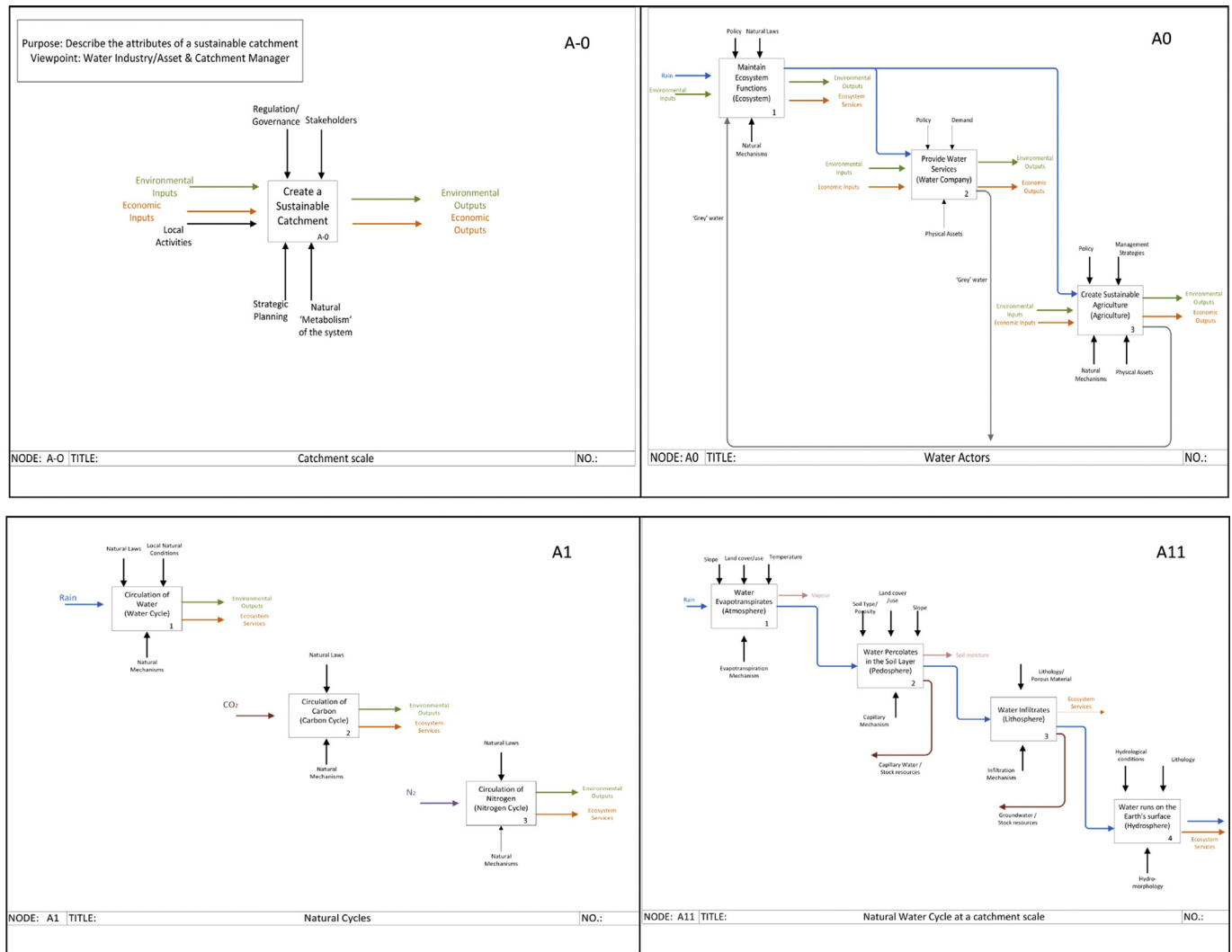


Fig. 5. IDEF0 model to describe the attributes of a sustainable catchment system. The ecosystem is analysed as an exemplar water actor and the natural water cycle as its main function.

each column represents the figures related to the inputs received by a single metabolic compartment of the system. Similarly, to the original PIOT, this procedure assists to the visualisation of the quantitative information relating to each component ('sector') of the catchment in the form of inter-component exchanges. The Catchment PIOT is essentially a matrix of flows, both physical and economic, circulating within the catchment boundaries.

The building blocks of the CM modelling schema are concrete steps (Fig. 6) that synthesise a new approach to asset management and to the representation of catchment systems. The paper focuses on the design and the underpinning rules of the CM schema and does not elaborate on the use of indexes for flow accounting or computation of outputs for the Catchment PIOT. This work will be published by the authors in a separate article.

4.2. The catchment metabolism schema in a water company

Applying the CM schema in practice requires the input from a number of experts, as for the needs of this transdisciplinary methodology a wide spectrum of expertise is synthesised. Fig. 7 demonstrates the types of experts and their individual contributions for the design and application of the Catchment Metabolism schema.

The practical application of the schema is a rather comprehensive process which requires collaborative action to be taken and the input from multiple experts. Throughout the process, an asset manager and a catchment expert are heavily involved. These roles can be fulfilled by individuals or teams. Their common tasks include the definition of the scope of the application and the identification of the main water actors in the catchment, i.e. of the catchment metabolism. Their individual tasks reflect their particular skills knowledge and are also aligned with the input from other company or external experts. For their individual tasks, the Asset Manager is responsible for the construction of the matrices that represent the outputs of individual sectors or activities within the catchment boundaries, while the Catchment Expert develops the accounting mechanisms for the computations of the outputs, making use of water accounting techniques.

For the creation of the Catchment PIOT and the IDEF0 model, a number of experts are required in order to perform the break-down of the water-related industries into their sectors and define their structural features (inputs, outputs, controls, mechanisms) respectively. For the case study presented in this work, the expertise of an environmental analyst, an operations manager and an agricultural expert are required for the analysis of the building blocks of the three main water actors identified within the given

Table 1

The catchment Physical Input-Output Table (PIOT), for a sector x sector matrix.

	Ecosystem functions				Water services					Agriculture					
	Water cycle				Urban water cycle					Annual cropping			Livestock		
	Atmosphere	Hydrosphere	Pedosphere	Lithosphere	Abstraction	Water treatment	Water distribution	Wastewater distribution	Wastewater treatment	Irrigation	Harvest	Fertilising	Watering animals	Feed	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Atmosphere	1	X (1,1)												X (1,n)	
Hydrosphere	2		X (2,2)							X (2,10)				X (2,n)	
Pedosphere	3			X (3,3)										X (3,n)	
Lithosphere	4				X (4,4)	X (4,5)				X (4,10)			X (4,13)	X (4,n)	
Abstraction	5	X (5,1)				X (5,5)				X (5,10)			X (5,13)	X (5,n)	
Water treatment	6	X (6,1)					X (6,6)							X (6,n)	
Water distribution	7							X (7,7)		X (7,10)			X (7,13)	X (7,n)	
Wastewater distribution	8								X (8,8)					X (8,n)	
Wastewater treatment	9	X (9,1)								X (9,9)				X (9,n)	
Irrigation	10		X (10,2)	X (10,3)	X (10,4)						X (10,10)			X (10,n)	
Harvest	11											X (11,11)		X (11,n)	
Fertilising	12												X (12,12)	X (12,n)	
Watering animals	13		X (13,2)	X (13,3)	X (13,4)									X (13,n)	
Feed	14	X (14,1)	X (14,1)											X (14,n)	
		X (n,1)	X (n,2)	X (n,3)	X (n,4)	X (n,5)	X (n,6)	X (n,7)	X (n,8)	X (n,9)	X (n,10)	X (n,11)	X (n,12)	X (n,13)	X (n,14)

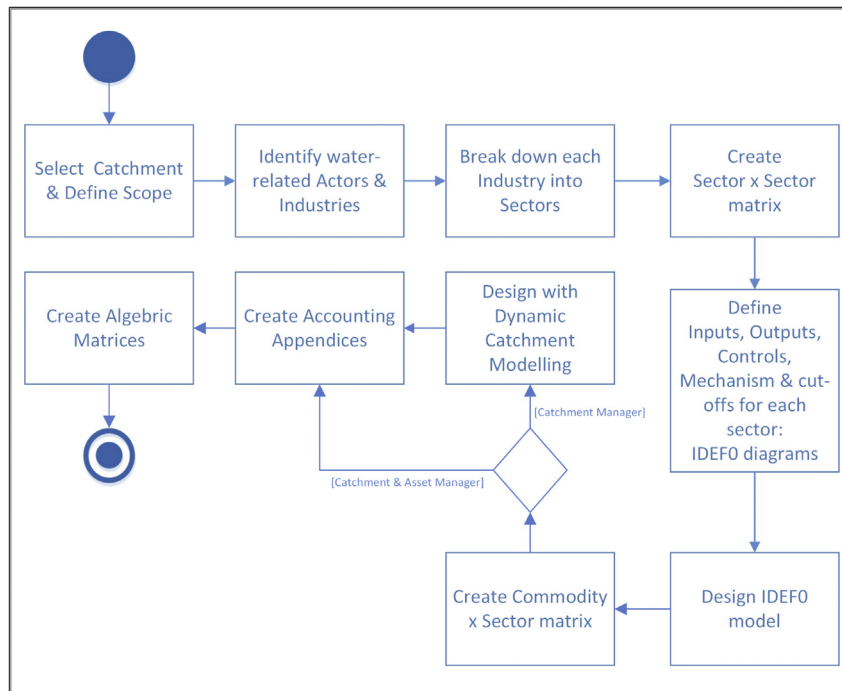


Fig. 6. Steps undertaken to produce the catchment metabolism modelling schema for a selected catchment.

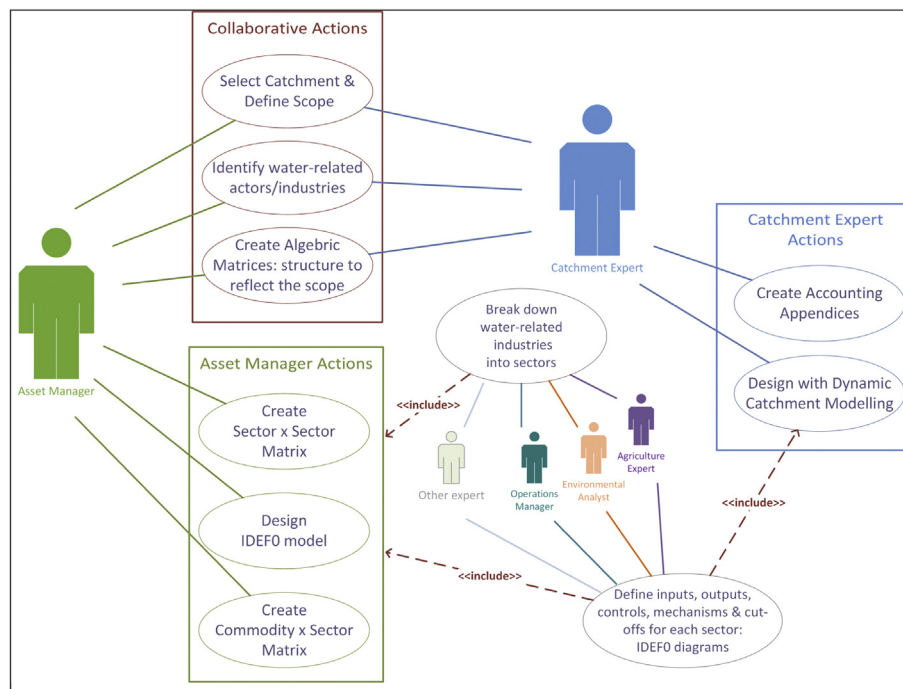


Fig. 7. Use Case Diagram on the expert input for the production and implementation of the catchment metabolism schema within a water company. The Unified Modelling Language (UML) has been used the basis for the construction of this diagram; derogations from the UML rules were made for the accommodation of the scope of the work and for better communication with the audience.

system. The further development of the Catchment Metabolism schema and its application to diverse catchment typologies—in terms of their water sectors and activities—will require the involvement and input from different experts. That would serve the creation of knowledge blocks and would ensure the quality of the data displayed and produced.

The data produced by the assembly of the separate IDEF0 diagrams constitute the heart of the entire schema providing essential insights in the subsystems of the catchment under consideration. The Asset Manager will then pull the separate IDEF0 diagrams together in order to create the IDEF0 model and the Input-Output matrices for sectors and commodities. The data gathered for the

development of the IDEF0 model will serve as the basis for the construction of a systems dynamic model by the Catchment Expert. The outputs of this type of model will produce the information for the Catchment PIOT.

5. Discussion

The paper adds to the limited literature on the systemic approaches used to date for the integration of natural capital in the asset management portfolio of the water sector. The work stresses the importance of assessing water-related issues and decision-making at a catchments scale and demonstrates a structured approach to achieve this. Relevant research undertaken in other scales, such as urban, peri-urban or community levels, would provide insights in methodological advancements that would then be re-adjusted to inform the catchment-based approaches.

The coherent structure of the Catchment Metabolism modelling schema could inform the design of integrated catchment management strategies and assist the successful implementation of catchment-based initiatives. It introduces new patterns in conceptualising and modelling a catchment, collecting data and displaying information which allows for a better understanding of the sub-systems of complex systems and facilitates communication among stakeholders and regulatory bodies. The creation and further development of systemic approaches at this scale would respond to the need for prove effective tools which support strategic decision-making and would be particular interest to multiple stakeholders, ranging from water companies to policy-makers.

The systemic approach introduced is concise, scalable, flexible, re-producible and easy to use, as it is a step-by-step process. Although the focus of the paper is the water cycle, the underpinning methodology of the modelling schema can be applied to other studies looking at the water, carbon or nitrogen natural cycles. In addition, the current work presents its application at a wide catchment (water basin) scale. However, it can be applied to diverse catchment systems, varying in size (from sub-catchments to tributaries) and metabolisms. The scope and scale of application may vary, but the underpinning rules applied and the steps undertaken would remain the same. Thus, for the reproduction of the approach for other catchment systems, the experts involved would need to follow the structured step-by-step procedure outlined in the paper. The identification of the main actors of the catchment, their activities and interlinked relations would lead to the definition of its metabolism. The outputs for different catchment systems would vary dependant on the catchment's typology (natural setting and conditions) and metabolic compartments. The outputs would be further differentiated upon the performance of arithmetic calculations-based on water accounting techniques and indices.

The clearly defined building blocks of the CM schema make it modular: parts of the methodology can be disseminated to experts and then assembled to formulate the modelling schema. The tools utilised to synthesise the methodology contribute to the delivery of a coherent approach and can all be reproducible from the actors involved in asset and catchment management projects. Based on the popular concept and methodology of environmental input-output analysis (E-IO) the CM modelling schema opens the black box of natural flow accounting for business purposes. The Catchment PIOT captures the flows occurring both in the interface of biosphere and technosphere, but also within the biosphere alone.

Recent works (Pedro-Monzonís et al., 2016; Hein et al., 2015; Dimova et al., 2014; Obst and Vardon, 2014; Čuček et al., 2012) have demonstrated that the environmental and water accounting approaches, although simple in nature, are resource intensive and require the collection of data from multiple stakeholders and the aggregation of information at different scales. The application of

the CM modelling schema suffers from the same issues while the dubious availability of the datasets and the aggregation of information in a uniform format increases its complexity. The transdisciplinary character of such works stress the need for knowledge exchange and alignments of perspectives. More exemplar case study applications may provide further practical insights and facilitate the integration of the methodology in every day practice. Nevertheless, the introduction of functional modelling (through IDEF0) for data collection and information display facilitates these tasks and creates common ground for information display in a concise way. The inclusion of information regarding the controls and mechanisms of a system or a process allows for holistic views and approaches to be implemented.

The complexity of the endeavour of modelling aspects of the water cycles has been highlighted in literature (e.g. Valipour et al., 2015) although the value of the existing hydrological models for decision-making purposes is challenged (Haberlandt et al., 2009). The transparency of the CM modelling schema enables the detailed mapping of each of the subsystems of a catchment system and highlights the complexities of a catchment system which can be modelled and addressed by hydrological models. It therefore enables the integration of the outputs of existing hydrological models into policy and decision-making. It can also highlight areas where more robust models are required. It can also assist identifying data priorities, the optimum granularity level for data gathering, along with the most appropriate data formats for value adding activities, such as the improvement of available models.

There is an emerging consensus that accounting for environmental assets-including water resources - would provide a valuable, comprehensive and integrated information set to guide environmental management and monitoring and policy-making (Hein et al., 2015; Obst and Vardon, 2014) in public and corporate levels. Likewise, as Richter et al. (2003) suggests, the use of environmental flows research allows for a clearer explanation about the distinction between ecosystem functions and ecosystem services. Indeed, the methodology presented sheds light on this confusion: the function occurs as part of the stakeholder 'ecosystem' and the outputs of the function are either environmental flows –those that return to the environment- or ecosystem services – which are the 'economic flows' of the biosphere to the technosphere, therefore, the contribution of the environment to the human wellbeing. Making use of the literature on the economic valuation of ecosystem services, economic values and costs can be estimated for all quadrants of the Catchment PIOT. Therefore, it can serve as the ground to build an economic model. The supplementary use of Earth System Modelling (Arbault et al., 2014) would provide further details on how flows are circulated within the catchment boundaries, especially for those 'critical' flows for the environment, e.g. stock flows.

6. Conclusions

The research described in this paper provided a novel, structured and systemic approach for asset management schemes in the water sector. The approach enables the integration of natural assets in the water sector's portfolio and contributes to the limited literature of the approaches on transparent flow accounting and industrial reporting. The Catchment Metabolism is a modelling schema built on a transdisciplinary basis. Drawing from literature on ecosystem functions, their deriving services and catchment-based water resources management, the underpinning research shows the need for synthesis of concepts and methods for integrated strategic planning in the water sector.

The building blocks of the methodology have been analysed and introduced via a selected case study. Following its clear principles

and stages, the modelling schema is reproducible for other catchments and can serve both asset and catchment management applications, whilst facilitating communication among experts and regulators. The structured methodology underpinning the modelling schema provides an opportunity for standardising an approach which allows water companies to explicitly account for natural capital and respond to current policy demands for resilient and long-term investment planning.

After having introduced the conceptual part of the Catchment Metabolism modelling schema and the principles of its underpinning methodology, future work will focus on finalising the selection of the metrics and indexes that best describe catchment flow accounting and can convert the Catchment Physical Input Output Table into a matrix of flows. Based on the principles of input output analysis and matrix algebra, the computation structure of the Catchment Metabolism will then be created, allowing for computations to be performed. After the finalisation of the inventory stage, system dynamics modelling will be used in synergy with the Catchment Metabolism underpinning methods for the assessment of the environmental performance of selected asset management strategies. This would include the assessment of their environmental impacts and would contribute to the creation of region-specific characterisation factors.

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